LONG-TERM SOLAR IRRADIANCE VARIABILITY: 1984-1989 OBSERVATIONS

Robert B. Lee III

Atmospheric Sciences Division, NASA Langley Research Center
Hampton, Virginia 23665-5225

ABSTRACT

Long-term variability in the total solar irradiance has been observed in the Earth Radiation Budget Experiment (ERBE) solar monitor measurements. The monitors have been used to measure the irradiance from the Earth Radiation Budget Satellite (ERBS) and the National Oceanic and Atmospheric Administration NOAA-9 and NOAA-10 spacecraft platforms since October 25, 1984, January 23, 1985, and October 22, 1986, respectively. Before September 1986, the ERBS irradiance values were found to be decreasing -0.03% per year. This period was marked by decreasing solar magnetic activity. Between September 1986 and mid-1989, the irradiance values increased approximately 0.1%. The latter period was marked by increasing solar activity which was associated with the initiations of the sunspot cycle number 22 and of a new 22-year Hale solar magnetic cycle. Therefore, long-term solar-irradiance variability appears to be correlated directly with solar activity. The maximum smoothed sunspot number occurred during September 1989, according to the Sunspot Index Data Center. Therefore, the recent irradiance increasing trend should disappear during early 1990 and change into a decreasing trend if the observed irradiance variability is correlated more so with the 11-year sunspot cycle than the 22-year Hale cycle.

The ERBE solar monitors are the most recent pyrheliometers, active cavity radiometers, to be placed into orbit to continuously measure the irradiance. They are sensitive to irradiance in the 0.2 to 50+ micrometer spectral broadband region. The precision of a single ERBS irradiance measurement has been estimated to be less than 0.02%. It is expected that at least one of the three monitors will extend the ERBE irradiance time series into the year 1998.

In this paper, the ERBE irradiance values are presented and compared with sunspot activity for the 1984-1989 period. The ERBE values are compared with those available from the Nimbus-7 and Solar Maximum Mission spacecraft experiments.

1. INTRODUCTION

At the top of the atmosphere, the Earth Radiation Budget Experiment (ERBE)[1] is measuring the three components of the Earth radiation budget: the incoming total solar irradiance, the Earth/atmosphere-reflected solar irradiance, and the Earth/atmosphere-emitted radiant exitance. The irradiance measurements are designed to detect long-term changes in the irradiance magnitude and to produce reference measurements for the calibration of the ERBE scanning and nonscanning radiometers. The reference measurements are obtained using the solar monitor[2]. The monitors are located on the Earth Radiation Budget Satellite (ERBS), NOAA-9, and NOAA-10 spacecraft platforms which were launched October 5, 1984, December 12, 1984, and September 17, 1986, respectively. The monitors are active-cavity-type radiometers and recent versions of the active-cavity radiometer irradiance monitors (ACRIM) which were flown on the Solar Maximum Mission (SMM) spacecraft.

The monitors' total solar irradiance measurements are performed every 14 days during a single orbit for a 128- to 640-second period. The measurement period is divided into 64-second cycles. Each cycle consists of a 32-second solar irradiance measurement phase and a 32-second reference (near zero irradiance) phase. During the irradiance phase, the shutter of the monitor is opened and the solar irradiance is sensed by the monitor. During the reference phase, the shutter is closed and the near zero irradiance, which is emitted by the back of the aluminum shutter, is sensed. During the measurement period, the Sun drifts through the unobstructed field of view of the monitor which is $\pm$ 4.6 angular degrees. The angular position of the Sun with respect to the optical axis has to be considered since the response of the monitor varies as the cosine of the angular position. The data reduction model and solar monitors are described by Lee et al.[2]

2. ERBE SOLAR IRRADIANCE MEASUREMENTS

In Figure 1, the ERBS, NOAA-9, and NOAA-10 irradiance values, normalized to 1 astronomical unit, are presented as a function of time. The irradiance values are available from the National Space Science Data Center (NASA Goddard Space Flight Center, Greenbelt, MD 20771) and the NOAA Solar Terrestrial Data Center[3]. The ERBS time series covers the October 25, 1984, through August 30, 1989, period, while the NOAA-9 one covers the January 23, 1985, through August 30, 1989, period. The NOAA-10 data set covers the October 22, 1986, through April 1, 1987, period. The mean irradiance values for the ERBS, NOAA-9, and NOAA-10 time series are 1365.1 $\pm$ 0.6, 1364.8 $\pm$ 0.8, and 1363.2 $\pm$ 0.3 Wm^{-2}, respectively. The bars on each time series denote the measurement precisions of 0.2, 0.5, and 0.8 Wm^{-2} for the ERBS, NOAA-9, and NOAA-10 monitor data sets, respectively. The absolute uncertainty of the monitor measurements has been estimated to be 2.7 Wm^{-2} (0.2%).

In Figure 1, three features are significant. The first feature is that the NOAA-10 irradiance data set covers only 6 months. On April 1, 1987, its shutter mechanism failed. During pre-launch tests, the mechanism exhibited operational problems. The ERBS and the NOAA-9 monitors have not exhibited any operational problems with the shutter. The second feature is that the NOAA-10 mean irradiance value is approximately 2 Wm^{-2} lower than the mean for either the ERBS or NOAA-9 data set. The absolute uncertainty of the monitor has been estimated to be 2.7 Wm^{-2}. Therefore, the agreement among the three data sets is excellent and well within 0.2%. The third most obvious feature is the long-term decreasing and increasing trends. In the following paragraphs, the long-term trends are discussed using the ERBS and NOAA-9 irradiance data sets.

In Figure 2, the NOAA-9 irradiance values are presented for the 1985 through 1989 period. The previously mentioned decreasing and increasing trends are highlighted by the second order polynomial fit through the data. Applying least squares analyses to the data, the irradiance was found to be decreasing at a rate of -0.05% per year before September 1986[4] and increasing at a rate of +0.03% after August 1986[5]. The correlation coefficients for the decreasing and increasing trends are 0.52 and 0.42, respectively. In Figure 1, it can be seen that the NOAA-9 data set exhibited more scatter than the data sets for the ERBS and NOAA-10, especially after 1986. It is believed that the increased scatter was caused by the spacecraft solar panels occasionally interfering with the solar monitor field of view. In Figure 1, the measurement precision bars indicate that the ERBS data set is the best one to evaluate the irradiance trends which are prominent in both ERBS and NOAA-9 data sets.

In Figure 3, the ERBS irradiance values are presented for the 1984 through 1989 period. The second order polynomial fit accents the long-term decreasing and increasing trends which were noticeable in the NOAA-9 data. Since the precision of the ERBS set is better than that for NOAA-9, the ERBS fit can be used to establish mid-1986 as the time of irradiance minimum. Applying the method of least squares, the slope of the ERBS decreasing trend was found to be -0.03% per year[4,6] before September 1986. After August 1986, the slope of the increasing trend was found to be approximately +0.03%[5]. For the two periods, the correlation coefficients were found to be 0.56 and 0.63, respectively. In the ERBS and NOAA-9 data sets, the magnitude of the irradiance increased approximately 1.3 W/m^{-2} (0.1%) between 1986 and 1989. Both the increasing and decreasing trends have been observed in the Nimbus-7[7] and SMM[8] irradiance data sets. These trends were not caused by instrument degradation[5]. They indicate solar variability.

In Figure 3, the ERBS irradiance values are compared with smoothed international sunspot number[9], an index of solar magnetic activity. The smoothed sunspot number represents a 12-month running mean. On a long-term scale, the comparison emphasizes that the irradiance varies directly with the sunspot number. The minimum sunspot number occurred during September 1986[10] which marked the end of sunspot cycle 21. Thereafter, cycle 22 started with rapidly increasing sunspot activity. September 1986 also marked the beginning of a new 22-year Hale magnetic cycle. Cross correlating the ERBS data set with the sunspot numbers, the method of least squares yields a positive correlation coefficient of +0.57 for the decreasing trend and a positive correlation coefficient of +0.59 for the increasing trend between irradiance variability and sunspot activity. It is believed that the resulting correlation coefficients are reasonable when one considers that the irradiance varies inversely[2,7,8] with sunspot number over periods of the order of the 27-day rotational period of the Sun. In Figure 3, the two isolated, low ERBS irradiance values for December 21, 1988, and June 16, 1989, were caused by large sunspot groups crossing the solar disk. The sunspot blocking is considered to cause the irradiance to decrease as large numbers of sunspots drift across the solar disk into the effective field of view center and to cause the irradiance to increase as the sunspots drift out of the field-of-view[11]. Sunspots emit less energy than the surrounding photosphere because they are approximately 2000 degrees Celsius cooler. In the vicinity of sunspots, faculae are the bright features which emit more energy than the surrounding photosphere. On the short-term scale, sunspot blocking dominates faculae brightening[11,12]. On the long-term scale, faculae dominate because they have a significant longer lifetime than sunspots. The reader is referred to Willson and Hudson[8], Schatten[13], and Foukal and Lean[14] for reviews of efforts to model the long-term and short-term irradiance variability.

3. COMPARISONS AMONG ERBS, NIMBUS-7, AND SMM IRRADIANCE DATA SETS

In Figure 4, the ERBS, Nimbus-7 channel 10c, and SMM ACRIM irradiance data sets are presented. The bars denote the estimated absolute accuracy of each set. The Nimbus-7 and SMM data sets were obtained from the National Space Science Data Center. There is reasonable agreement among the three data sets since they are found to be within approximately 0.5% of each other. The best accuracy characterization of any room temperature radiometer is its response in measuring the theoretical value of the Stefan-Boltzmann constant. The best room temperature experimental measurement of the Stefan-Boltzmann constant differed from the theoretical value by 0.3%[15]. The ERBS, Nimbus-7, and SMM radiometers are room temperature devices. At the solar irradiance value of 1365 Wm^{-2}, the absolute accuracy would be about 4 Wm^{-2}. Therefore, the differences between the radiometers which were characterized independently would not

be expected to agree much closer than 0.3%. It should be pointed out that the long-term measurement precision and the bias constancy among the data sets are just as important as the absolute accuracy in characterizing the long-term variability of solar irradiance. The 5 years of overlap among the three experiments will allow additional precise comparisons to be performed among the irradiance time series as was done by Mecherikunnel et al.[16] for the 1984-1987 period.

The ERBS data set exhibited comparably more scatter than the Nimbus-7 and SMM because the ERBS values represent instantaneous values and not daily averages. On a single day, the Nimbus-7 data sampling is 7 times greater than the ERBS sampling. Therefore, Nimbus-7 scatter statistically should be approximately one-third of that for the ERBS. The SMM daily sampling is 200 times greater than that for the ERBS. Therefore, the SMM scatter should be statistically one-fourteenth of that for the ERBS. The sampling rates are important when the magnitude of the scatter in the data is considered. For example, the SMM experiment did not track the Sun between November 1980, when its solar tracking mechanism failed, and April 1984 when the mechanism was repaired. During this period, its measurement sampling was reduced by approximately 99.95%[17] compared to the samplings before and after the non-tracking period. Accordingly, the SMM scatter was statistically higher during the November 1980 to March 1984 period as indicated in Figure 4. Sampling affected the Nimbus-7 data set also. For example, the Nimbus-7 scatter decreased noticeably after September 1983 when its sampling rate was increased to daily.

The ERBS and NOAA-9 data sets, with considerably lower sampling rates, exhibited similar long-term irradiance trends which are found in the Nimbus-7 and SMM sets. Applying the method of least squares, the Nimbus-7 and SMM data sets yielded decreasing irradiance trends of -0.013% and -0.016% per year before September 1986 with correlation coefficients of 0.56 and 0.63, respectively. After August 1986, the rates for the increasing irradiance trends were found to be +0.04% and +0.02% per year for the Nimbus-7 and SMM data sets with correlation coefficients of 0.69 and 0.48. With lower sampling rates, the ERBS and NOAA-9 sets were found to have similar trend results which were described earlier.

According to Sunspot Index Data Center, a smoothed maximum sunspot number of 165 occurred during December 1979, maximum for sunspot cycle 21. A maximum value of 161 occurred during September 1989, maximum for sunspot cycle 22. If irradiance variability can be correlated strongly with sunspot number, then the magnitude of the irradiance should be essentially identical for December 1979 and September 1989. To explore this concept, the ERBS irradiance variability was characterized with cosine functions for 11- and 22-year cycles. The cosine parameters for the 11-year characterization are described in the following sentences. During the periods of decreasing sunspot numbers for sunspot cycles 21 and 22, I have assumed that (1) the period of the cosine function is equal to twice the time differential between December 15, 1979, and September 15, 1986; (2) the amplitude of the cosine function is equal to 0.05% of the mean irradiance magnitude; and (3) there is zero phase angle between the irradiance and sunspot variability. During the periods of increasing irradiance for sunspot cycles 21 and 22, I have assumed that (4) the period is equal to twice the time differential between September 15, 1986, and September 15, 1989; (5) the amplitude is equal to 0.05% of the mean irradiance value; and (6) the phase angle is equal to zero. For the 22-year characterization, the period is assumed to be twice those for the 11-year ones with an amplitude which is equal to 0.15% of the mean irradiance value.

The resultant cosine characterizations of the ERBS data are presented in the lower portion of Figure 5. Both the 11-year and 22-year characterizations fit the ERBS

data. The ERBS data set does not extend back to the 1979 through 1984 period. It cannot be used to evaluate the characterizations for that period. Therefore, the characterizations are compared with the longer Nimbus-7 and SMM data sets. Both the 11-year and 22-year characterizations provided good fits to the SMM data set. The SMM data set cannot be used to clearly identify the period of the long-term variability as 11 or 22 years. However, the comparisons with the Nimbus-7 data set suggest that the irradiance variability correlates closer with the 11-year cycle than the 22-year one. Therefore, it is reasonable to assume that the irradiance variability follows an 11-year cycle. Since the SMM experiment failed during late 1989, the Nimbus-7 and ERBE data sets will have to be relied upon to verify the 11-year irradiance variability and to detect possible 22-year variability.

4. CONCLUSIONS

The ERBS, NOAA-9, and NOAA-10 solar monitors have been used to derive the magnitude of the total solar irradiance, normalized to 1 astronomical unit, between 1365 and 1363 Wm^{-2} which fall within the 0.2% (2.7 Wm^{-2}) estimated measurement accuracy. The long-term measurement precisions of the monitors were demonstrated by their ability to detect irradiance variability in the 0.02% to 0.05% per year rate range. The observed 1984-1986 decreasing and 1986-1989 increasing trends are of solar origins and represent irradiance variability which is directly correlated with solar magnetic activity associated with the 11-year sunspot cycle.

The variability has been measured at the 0.1% level between sunspot minimum for sunspot cycle 21 and maximum for cycle 22. Comparisons of the Nimbus-7 irradiance magnitudes near sunspot maxima for cycles 21 and 22 indicated that the irradiance variability may differ during the remainder of cycle 22 and during cycle 23 from that which was observed during the 1979-1989 period. Therefore, it is important that the ERBE irradiance measurements be extended into the late 1990's in order to refine the characterization of long-term irradiance variability. The extension of the irradiance data set will have to be carried out by at least one of the three ERBE monitors because the SMM experiment was terminated in late 1989 and because the aging Nimbus-7 experiment may experience a failure in the near future similar to the one which occurred during September 1989.

5. REFERENCES

1. B. R. Barkstrom, E. F. Harrison, and R. B. Lee III, "The Earth Radiation Budget Experiment (ERBE) Preliminary Seasonal Results," Eos, vol. 71, pp. 297-305, 1990.
2. R. B. Lee III, B. R. Barkstrom, and R. D. Cess, "Characteristics of the Earth Radiation Budget Experiment Solar Monitor," Applied Optics, vol. 26, no. 7, pp. 3090-3096, 1987.
3. H. E. Coffey, Solar-Geophysical Data Comprehensive Reports, National Oceanic and Atmospheric Administration (Boulder, Colorado), report no. 538, part II, pp. 101-113, June 1989.
4. R. B. Lee III, M. A. Gibson, S. M. Natarajan, "Total Solar Irradiance Values Determined Using Earth Radiation Budget Experiment (ERBE) Radiometers," New Developments and Applications in Optical Radiometry, editors N. P. Fox and D. H. Nettleton, Institute of Physics Conf. Series no. 92, Bristol and Philadelphia, pp. 129-132, 1989.

5. R. B. Lee III, M. A. Woerner, M. A. Gibson, S. Thomas, and R. Wilson, "Total Solar Irradiance Variability: 5 Years of ERBE Date," Proc. of July 23-27, 1990 Seventh Conf. on Atmospheric Radiation, American Meteorological Society, Boston, MA, 1990 (In Press).
6. R. B. Lee III, B. R. Barkstrom. E. F. Harrison, M. A. Gibson, S. M. Natarajan, W. L. Edmonds, A. T. Mecherikunnel, and H. L. Kyle, "Earth Radiation Budget Satellite Extraterrestrial Solar Constant Measurements: 1986-1987 Increasing Trend," Advances in Space Research, vol. 8, no. 7, pp. 11-13, 1989.
7. J. R. Hickey, b. M. Alton, H. L. Kyle, and D. Hoyt, "Total Solar Irradiance Measurements by ERB/Nimbus-7: A Review of Nine Years," Space Science Reviews, vol. 48, pp. 321-342, 1988.
8. R. C. Willson and H. S. Hudson, "Solar Luminosity Variations in Solar Cycle 21," Nature, vol. 332, pp. 810-812, 1988.
9. A. Koeckelenberg, Sunspot Bulletin, Sunspot Index Data Center, Brussels, Belgium, May 1, 1984 through February 1, 1990.
10. A. Koeckelenberg, Sunspot Bulletin, Sunspot Index Data Center, Brussels, Belgium, March 1988.
11. H. S. Hudson, "Energy Balance in Solar Active Regions: the Dip of April 1985," Advances in Space Research, vol. 6, no. 8, pp. 81-83, 1987.
12. R. C. Willson, S. Gulkis, M. Jansen, H. S. Hudson, and G. A. Chapman, "Observations of Solar Variability," Science, vol. 211, pp. 700, 1981.
13. K. H. Schatten, "A Model for Solar Constant Secular Changes," Geophysical Research Letters, vol. 15, pp. 121-124, 1988.
14. P. Foukal and J. Lean, "An Empirical Model of total Solar Irradiance Variation Between 1874 and 1988," Science, vol. 247, pp. 556-558, 1990.
15. J. M. Kendall, and M. Berdahl, "Two Blackbody Radiometers of High Accuracy," Applied Optics, vol. 9, no. 5., pp. 1082-1091, 1970.
16. A. T. Mecherikunnel, R. B. Lee III, H. L. Kyle, and E. R. Major, "Intercomparisons of Solar Total Irradiance Data from Recent Spacecraft Experiments," J. Geophysical Research, vol. 93, no. D8, pp. 9503-9509, 1988.
17. R. C. Willson, H. S. Hudson, C. Frohlich, and R. W. Brusa, "Long-term Downward Trend in total Solar Irradiance," Science, vol. 234, pp. 1114-1117, 1986.

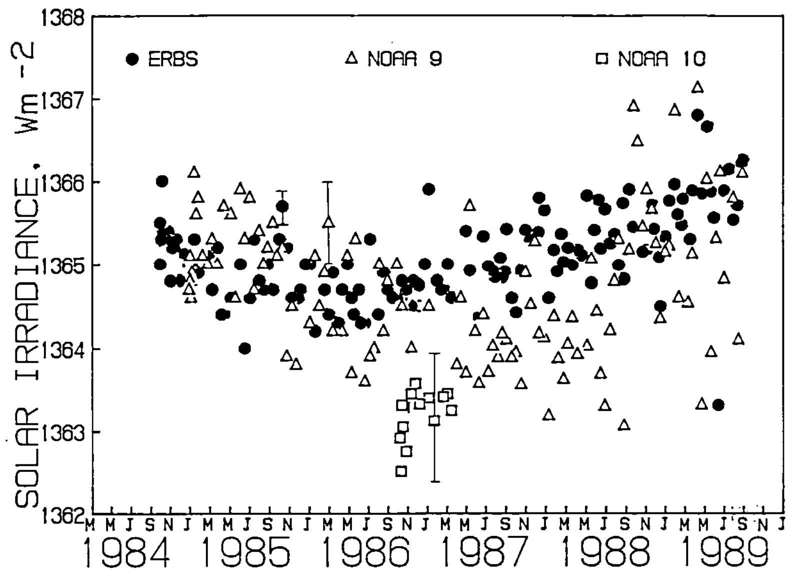

Figure 1. ERBS, NOAA-9, and NOAA-10 solar monitor irradiance measurements presented for the October 1984 through August 1989 period. The bars denote the measurement precisions for each data set.

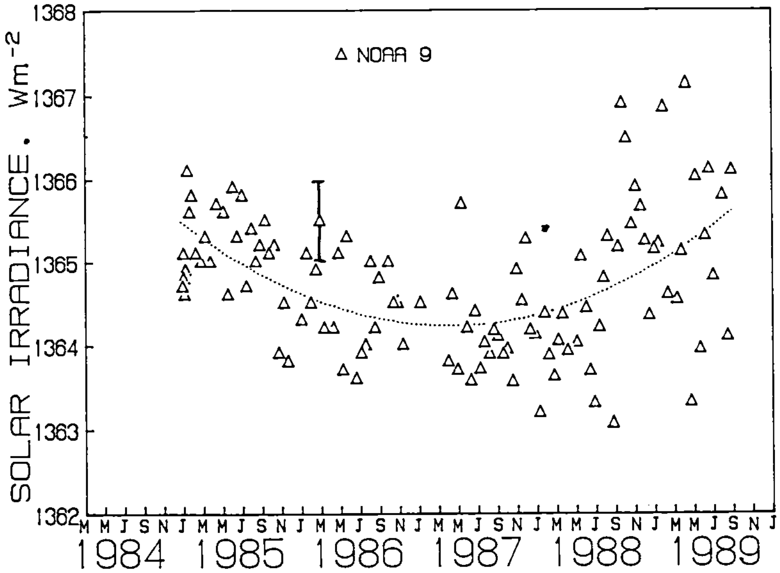

Figure 2. NOAA-9 solar monitor irradiance values for the January 23, 1985, through August 30, 1989, period. The curve represents a second order polynomial fit through the values. The bar denotes the typical measurement precision of 0.5 Wm^{-2}.

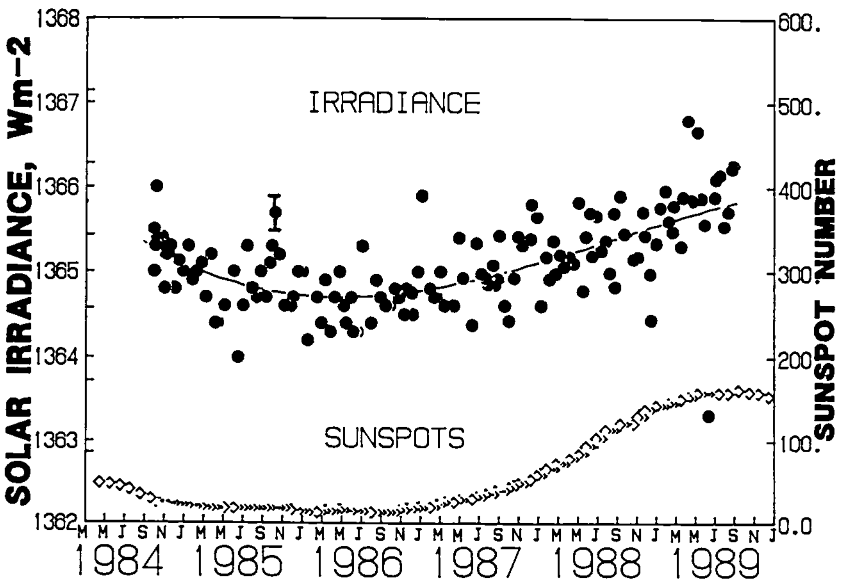

Figure 3. ERBS solar monitor irradiance values are presented for the October 25, 1984, through August 30, 1989, period. The bar denotes a typical measurement precision of 0.2 Wm^{-2}. ERBS irradiance values are compared with smoothed international sunspot number.

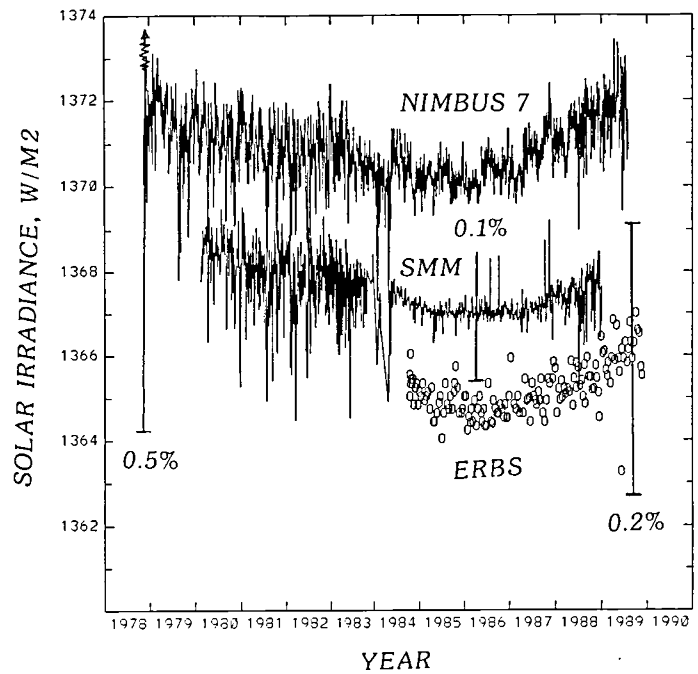

Figure 4. Solar irradiance values from the ERBS, Nimbus-7, and SMM experiments are compared. The bars denote the absolute accuracies of the irradiance data sets.

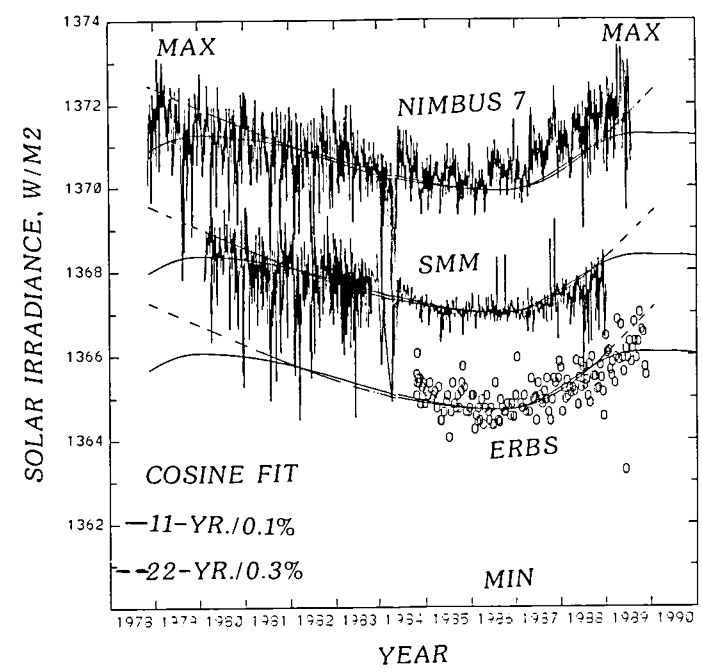

Figure 5. Cosine characterizations of irradiance variability are compared with the ERBS, Nimbus-7, and SMM irradiance data sets. The 11-year characterization assumes a 0.1% change in the irradiance between sunspot minimum and maximum, while the 22-year characterization assumes a 0.3% change in irradiance between minimum and maximum Hale magnetic activity.